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BeppoSAX Observations of the Atoll X-Ray Binary 4U 0614+091

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Abstract. We report the first simultaneous measurement of the broad band X-ray (0.3-150 keV) spectrum of the neutron star x-ray binary 4U 0614+091. Our data confirm the presence of a hard x-ray tail that can be modeled as thermal Comptonization of low-energy photons on electrons having a very high temperature, greater than 220 keV, or as a non-thermal powerlaw. We detected a spectral feature that can be interpreted as reprocessing, via Compton reflection, of the direct emission by an optically-thick disk and found a correlation between the photon index of the power-law tail and the fraction of radiation reflected which is similar to the correlation found for black hole candidate x-ray binaries and Seyfert galaxies.

Key words: accretion, accretion disks — stars: individual (4U 0614+091) — stars: neutron — X-rays: stars

1. Introduction

The x-ray source 4U 0614+091 was discovered in the Uhuru survey and was localized by Copernicus (Willmore et al. 1974). The source is an x-ray burster (Swank et al. 1978) and, thus, contains a neutron star. The luminosity of the x-ray bursts constrains the distance to be within 3 kpc (Brandt et al. 1992). Classification of 4U 0614+091 as an atoll source was suggested by Singh & Apparao (1994) and confirmed by Mendez et al. (1997). New study of the source has been stimulated by the discovery of high frequency quasi-periodic oscillations (QPOs) in the persistent emission of this source (Ford et al. 1997) and of a hard x-ray tail extending to at least 100 keV (Ford et al. 1996).

Here, we report on observations of 4U 0614+091 obtained with the narrow field instruments (NFIs) on board the BeppoSAX satellite (Boella et al. 1997). We have obtained the first simultaneous measurement of the broad band x-ray spectrum of 4U 0614+091, extending from soft x-rays to hard x-rays (0.3–150 keV) and are able to place strong constraints on the spectrum of the hard x-ray emission. We find that the continuum hard spectrum of 4U 0614+091 is well described by a powerlaw or thermal Comptonization with a reflection component. We find that the thermal Comptonization temperature and the lower bound on any exponential cutoff of the powerlaw model are both greater than 200 keV.

We also studied the relation between the reprocessed component and the intrinsic component. A correlation between the strength of reflection and the intrinsic spectral slope has been found for GX 339-4 (Ueda et al. 1994) and recently for Seyfert AGNs, 2 black holes candidate (BHC) X-ray binaries, and 2 X-ray bursters (Zdziarski et al. 1999). We find a similar relation for 4U 0614+091.

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2. Observations and Analysis

We performed a joint BeppoSAX/RXTE observation of 4U 0614+091 on 19-20 October 1998 for a total of 42.6 ks of on–source observing time in BeppoSAX (Piraino et al. 1999). Here, we use data from the four BeppoSAX Narrow Field Instruments (NFIs) in overlapping energy bands selected to give good signal to noise for this source: the Low Energy Concentrator Spectrometer (LECS) for 0.1–4 keV, the Medium Energy Concentrator Spectrometer (MECS) for 1.8–10 keV, the High Pressure Gas Scintillation Proportional Counter (HPGSPC) for 4–27 keV, and the Phoswich Detection System (PDS) for 12–200 keV. LECS and MECS data were extracted in circular regions centered on the source position using radii of 8' and 4' respectively, containing 95% of the source flux. The spectra have been rebinned to have at least 30 counts per channel, and the HPGSPC and PDS spectra were grouped using a logarithmic grid. A normalization factor has been included to account for the mismatch in the BeppoSAX instruments' absolute flux calibration. The

fit values of relative normalization are in good agreement with values typically observed (Cusumano et al. 1998).

For the total spectrum presented in Figures 1 and 2, we summed all of the 42.6 ks of data obtained in October 1998. To study the correlation of spectral slope with reflection, presented in Figure 3, we divided this observations into two intervals, based on luminosity, and also used data from an observation performed on 13-14 October 1996 available from the BeppoSAX archive, again divided into two intervals.

3. Spectral Results

We fit the 0.1–200 keV BeppoSAX spectrum of 4U 0614+091 with several single component continuum models: powerlaw, powerlaw with an exponential high energy cutoff, three different Comptonization models (Sunyaev & Titarchuk 1980; Titarchuk 1994; Poutanen & Svensson 1996), an exponentially cutoff powerlaw and a Comptonization model (Poutanen & Svensson 1996) each with added reflection (Magdziarz & Zdziarski 1995), thermal bremsstrahlung, several disk models, and each of these single component models with an added single temperature simple blackbody component. Each model also included absorption and a Gaussian line near 0.7 keV (Christian et al. 1994; White et al. 1997; Schulz 1999). Only the powerlaw (with or without an exponential cutoff) and Comptonization models gave close to acceptable fits ($\chi^2_\nu \simeq 1.33$) and in each case the fit was improved by addition of the blackbody component. In Table 1 we report the best fit parameters for the powerlaw model and the best fitting Comptonization model (Poutanen & Svensson 1996) both with and without reflection. The fit residuals of the models without reflection show a feature between 10 and 60 keV that disappears when reflection is added, see Figure 1. The two models with reflection provided the best fit with a significant improvement in χ^2_ν (see Table 1) relative to any other model.

The powerlaw with reflection model is the PEXRAV/PEXRIV model in XSPEC, which is an exponentially cut–off powerlaw spectrum with reflection (Magdziarz & Zdziarski 1995) from a disk. We assumed solar abundances and fixed at 60° the disk inclination angle. Adding an exponential cutoff does not improve the fit, either with or without reflection, and the cutoff energy is well above 200 keV. The Comptonization model with reflection is COMPPS, kindly supplied by Juri Poutanen. This code calculates radiative transfer and Comptonization in a two-phase disk-corona geometry (Poutanen & Svensson 1996). Reflection is calculated via the same method (Magdziarz & Zdziarski 1995) as for the PEXRAV model. We used the model to calculate thermal Comptonization and used an approximate treatment of radiative transfer using the escape probability for a sphere for the results presented in Table 1. The temperature

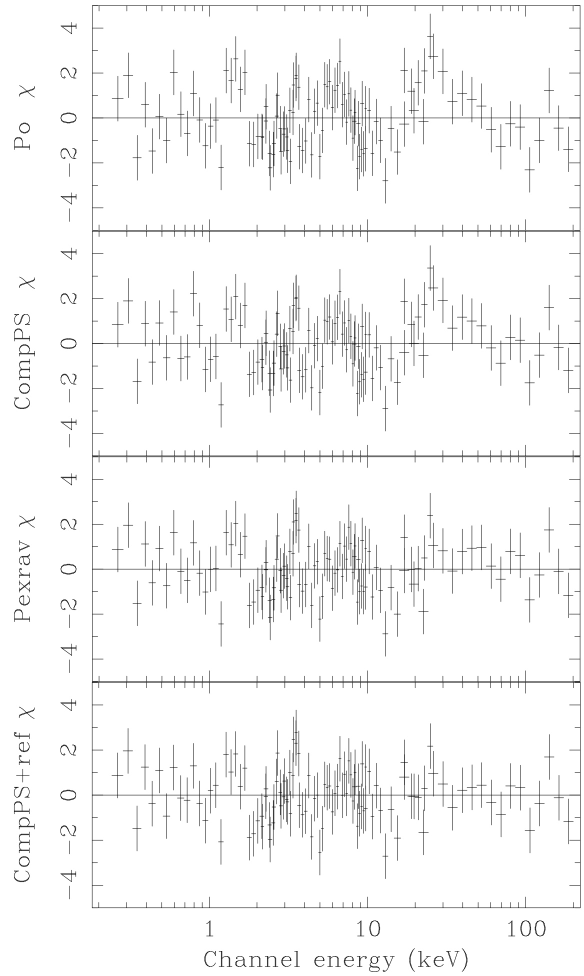

Fig. 1. Residuals for the models described in Table 1. For display, the energy bins are equal to the 1σ energy resolution.

of the input soft photon distribution is driven towards unexpectedly low values when left as a free parameter. We tried fixing this temperature to that of the lowest temperature soft photon source present in our spectral fit (the 0.27 keV blackbody), but were unable to obtain good fits. For both reflection models, the ionization parameter is consistent with zero, but is not well constrained. For the results presented in Table 1 and Figures 2 and 3, we used the PEXRAV model, which assumes a neutral reflecting medium, with no exponential cutoff. Figure 2 shows the BeppoSAX data and the various components of the fit using the PEXRAV model.

As the presence of an absorption edge is an inherent feature of reflection, before accepting the reflection as component of the model, we verified the presence in the spectrum of an absorption edge. Adding this feature to the powerlaw or Comptonization models, we found an improvement in the χ^2_ν and the same edge energy and optical depth ($E_{\rm edge} = 8.5\,{\rm keV}$, $\tau = 0.1$) found by Singh &

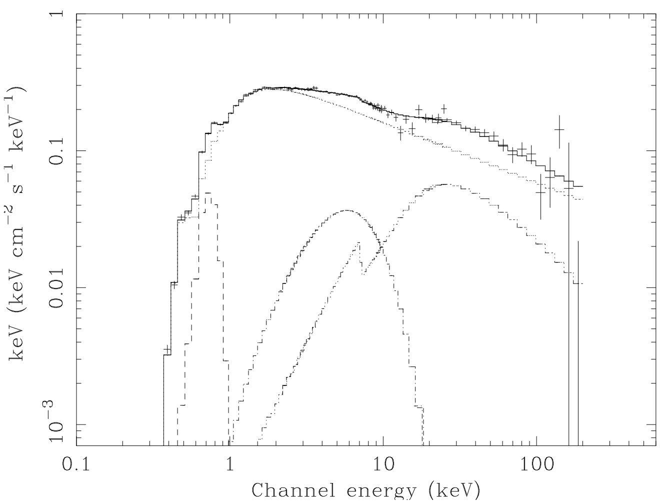

Fig. 2. LECS, MECS, HPGSPC and PDS unfolded averaged spectra, for the October 19–20, 1998 observation together with a model consisting of a powerlaw, reflection, a blackbody, and a low energy Gaussian line all with absorption. The total model fit is shown as a solid line, the powerlaw as dotted line, the reflection component as a dot-dot-dashed line, the blackbody component as a dot-dashed line, and the Gaussian line as a dashed line.

Table 1. Parameters for fits of the spectrum of 4U 0614+091

	PL	**Comp**	**PL with reflection**	**Comp with reflection**
$N_{\rm H}$	3.3±0.1	3.0±0.1	3.7±0.2	3.3±0.3
$E_{\rm g}$	0.71±0.03	0.70±0.03	0.66±0.04	0.65±0.05
σ	0.07±0.02	0.07±0.02	0.09±0.02	0.11±0.02
EW	88±33	90±20	140±64	140±60
Γ	2.33±0.02		2.44±0.03	
$kT_{\rm s}$		< 0.04		< 0.03
$kT_{\rm e}$		160±35		260^{+50}_{-40}
τ		0.26±0.1		0.10±0.03
$Refl$			0.90±0.25	0.45±0.25
$kT_{\rm bb}$	1.45±0.08	1.28±0.15	1.47±0.06	1.39±0.06
$F_{\rm bb}$	0.51±0.10	0.75±0.15	0.82±0.12	1.5±0.3
F	16.73	17.83	16.86	16.94
$F_{\rm un}$	40.33	38.39	47.93	34.17
$\chi^2_\nu(\nu)$	1.21 (561)	1.17(559)	1.09 (558)	1.08 (555)

Note — Given in the table are the absorption column density ($N_{\rm H}$) [in units of 10^{21} cm^{-2}], the centroid ($E_{\rm g}$) [keV], width (σ) [keV], and equivalent width (EW) [keV] of the low energy emission line, the photon index (Γ) of the powerlaw, and the temperature of the input seed photon distribution ($kT_{\rm s}$) [keV], the temperature ($kT_{\rm e}$) [keV] and optical depth (τ) of the Comptonizing electron cloud, relative reflection fraction (R), the temperature ($kT_{\rm bb}$) [keV] and flux ($F_{\rm bb}$) [10^{-10} erg cm^{-2} s^{-1}] of the blackbody, the absorbed (F) and unabsorbed ($F_{\rm un}$) flux [10^{-10} erg cm^{-2} s^{-1} for 0.1–200 keV], and the reduced chi square, χ^2_ν, and degrees of freedom (ν). All quoted errors represent 90% confidence level for a single parameter.

Apparao (1994) in a low state observation of 4U 0614+091 with EXOSAT.

Adding a Gaussian emission line to model iron K_α fluorescence did not improve the fit significantly and we place upper limits of 20–60 eV on the equivalent width for lines in the 6.4–8.1 keV range. While iron K_α fluorescence is commonly associated with reflection in AGN, the iron line emission found in Galactic BHC X-ray binaries in the low (hard) state is much less than that found in AGN (e.g. Zdziarski et al. 1998). This may be due to differences in the ionization state or geometry of the disk, Doppler broadening and relativistic changes in the line profile which make the line difficult to detect, or resonant Auger destruction (Ross, Fabian & Brandt 1996). All of these effects may also hold for neutron star X-ray binaries. In addition, the equivalent width of iron K_α for 4U 0614+091 is likely to be low since the equivalent width of iron K_α decreases approximately linearly with photon index Γ as result of the decrease in the number of incident photons with energy larger than the absorption edge energy for higher Γ (George & Fabian 1991; Vrtilek et al. 1993) and Γ is larger for 4U 0614+091 than for BHC x-ray binaries in the low (hard) state.

We found a blackbody component with temperature, $kT_{\rm bb}$, near 1.5 keV. As the Comptonization optical depth is small, the detection of the blackbody is consistent with an origin within the Comptonization region. We note that the blackbody flux found using COMPPS is twice that found using the powerlaw. Thus, it is unlikely that the blackbody component is a spurious feature due to approximation of the Comptonization spectrum with a powerlaw. Blackbody components have been found from 4U 0614+091 in the past, with kT ranging from 0.3 keV (Christian et al. 1994; Schulz 1999) to 1.7 keV (Singh & Apparao 1994; Barret & Grindlay 1995). Adding a second blackbody component to our model, we found that the second blackbody improves the fit slightly and has $kT = 0.27 \pm 0.03$ keV. Thus, two blackbody components may be simultaneously present in the spectrum of this source. Addition of the second blackbody does not significantly affect the other fit parameters. We also tried using the blackbody accretion disk models of Shakura & Sunayev (1973), Stella & Rosner (1984), and Mitsuda (1984). These models also gave good fits, but not better than the fits obtained with the simple blackbody.

Using the PEXRAV model in a total of four intervals over the two observations, we found that the amount of reflection and also the blackbody flux are correlated with the photon index (Fig. 3). The values found for the reflection coefficient are large. This may indicate that the photon flux irradiating the disk is larger than the observed flux as expected for relativistic electrons in an anisotropic reflection geometry (Ghisellini et al. 1991) or may simply

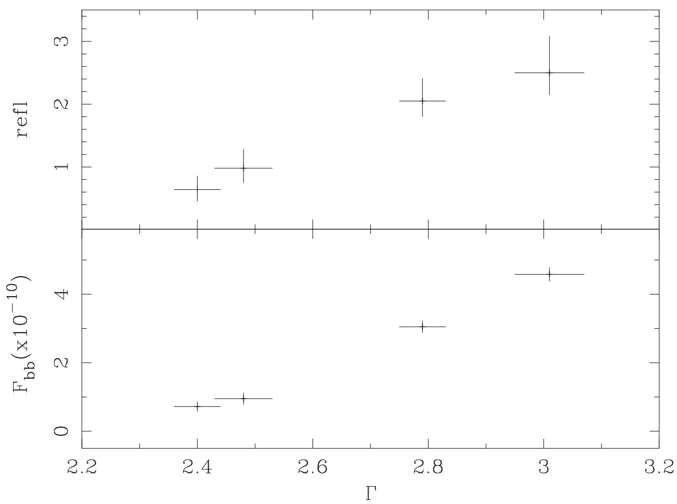

Fig. 3. Spectral parameters correlations. (a) Magnitude of reflection versus photon index. (b) Blackbody flux (erg cm^{-2} s^{-1}) versus photon index.

indicate that the inclination is less than 60°. The unabsorbed luminosity in the 0.1–200 keV band varied over the range $5.1 - 29.1 \times 10^{36} (\frac{d}{3\,\mathrm{kpc}})^2\,\mathrm{erg\,s^{-1}}$ in the four intervals.

4. Discussion

Before the BeppoSAX era, there were no x-ray burster observations with simultaneous energy coverage from 0.1–200 keV. This broad coverage is very important to accurately measure the x-ray spectrum. Using BeppoSAX, we find a spectrum for the x-ray burster 4U 0614+091 which can be described either with a powerlaw with no detectable cutoff below 200 keV or with a thermal Comptonization spectrum with an electron temperature in excess of 220 keV. As equally good fits are obtained in the two cases, we cannot determine whether the emission is due to a thermal or non-thermal process. If the emission is due to Comptonization, with either a thermal or non-thermal electron energy distribution, then the input soft photon distribution must peak at an energy well below that of any observed soft photon source; in particular, well below the temperature of the cooler (0.27 keV) blackbody component. Production of these soft photons must be addressed in any successful application of a Comptonization model to 4U 0614+091.

The only robust evidence for the presence of a black hole in an X-ray binary is a measurement of the mass of the compact object indicating a value greater than $3\,M_{\odot}$. While neutron stars have unambiguous x-ray observational signatures, such as type I X-ray bursts or coherent X-ray pulsations, black holes at best offer negative evidence: the absence of any clear neutron star characteristics. Several criteria have been proposed to distinguish black holes from neutron stars in x-ray binaries based on solely on their x-ray emission, but so far none has been found be truly unique to black holes. It has been proposed that two-component spectra, with a thermal component and an extended steep power-law component, are a signature of the presence of a black hole in a binary system (Laurent & Titarchuk 1999). Our data clearly show the presence of both a soft thermal component and a steep power-law component extending to at least 200 keV from an x-ray binary containing a neutron star. Again, a criterion proposed to distinguish black hole versus neutron star binaries based on their x-ray emission is found inadequate.

The spectrum we observe from 4U 0614+091 may also be compared to the proposal by Zdziarski et al. (1998) that very high energy cutoffs, $E_{\mathrm{cut}} \geq 100\,\mathrm{keV}$, and thermal Comptonization temperatures, $kT_{\mathrm{e}} \geq 50\,\mathrm{keV}$ are a signature for black holes. However, this criterion applies only to the hard state ($\Gamma < 2$) emission, while we found 4U 0614+091 in a softer state ($\Gamma = 2.45$). It would be of great interest to observe 4U 0614+091 with BeppoSAX while it is in a harder state to see if the spectrum still extends to high energies without a cutoff.

Our best deconvolution of the spectrum requires reflection from an optically-thick disk. Reflection models have worked very well in fitting broad bumps, between 10–60 keV, visible in the spectra of black hole candidates (Done et al. 1992; Gierliński et al. 1997; Zdziarski et al. 1998). For two other x–ray bursters, 4U 1608–522 and GS 1826–238, observed by Ginga in their hard (low) state the reflection model gave also good results (Yoshida et al. 1993; Strickman et al. 1996). The excellent broad band coverage of BeppoSAX gives strong evidence for reflection in the spectrum of 4U 0614+091. We find that the magnitude of the reflection and the flux of the blackbody component are both correlated with the photon index. Zdziarski et al. (1999) found a common correlation between strength of reflection and spectral slope in Seyfert AGNs, 2 black hole candidate X-ray binaries, and the X-ray bursters 4U 1608-52 and GS 1826-238. The correlation we find for 4U 0614+091 is similar in form but may be slightly displaced to higher values of the photon index. Additional high-quality broad-band spectra obtained with BeppoSAX would permit more detailed study of this correlation in the future.

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